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Wright-Patterson Air Force Base, Ohio

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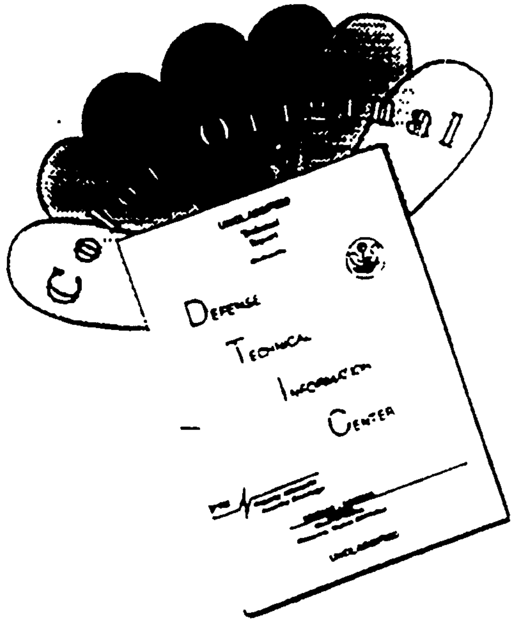

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THE COMBUSTION OF CONDENSED EXPLOSIVES (VV) IN THE CASE OF OVERLOADS

S. K. Ordzhonikidze, A. D. Margolin,
and P. F. Pokhil

(Moscow)

This work deals with the investigation of the combustion of solid, liquid, and water-filled systems in a field of inertial forces. The tests were conducted on a centrifuge with a radius of 4.5 cm at accelerations up to 2000 g. The samples were burned in a closed space at pressures up to 150 atm(tech.). The time of burning was determined by a pressure oscillogram.

The *solid composition* investigated in our work contained 15% rubber, 15% aluminum (particle dimensions up to 10 microns), and 70% ammonium perchlorate. The samples had a cross section area of 0.4 cm^2 and a length from 0.5 to 1.5 cm.

The tests showed that accelerations directed from the burning surface of the fuel into the gaseous phase do not influence the rate of burning. In the case of a reverse direction of acceleration the rate of burning is increased, and the increase in the rate (Δu) is proportional to the square root from the value of acceleration (a) and is decreased with the length of the sample (Fig. 1).

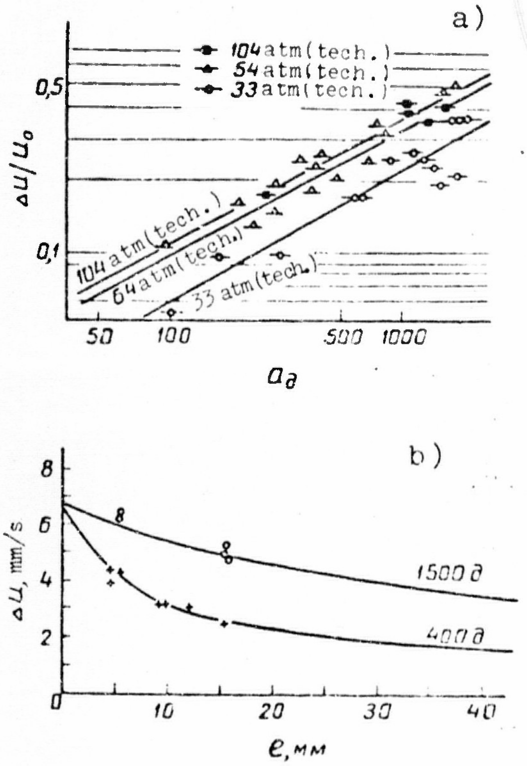

Fig. 1. Dependence of the rate of combustion on acceleration for samples with a length of 1.5 cm (a) and on the length of a sample at a pressure of p = 70 atm(tech.) and u_0 = 1.1 cm/s (b).

After the burning of the sample on the bottom of the cup in which it is found there remains a grayish slag, the particles of which have a specific weight of 2.8 g/cm^3. Chemical analysis showed that the slag does not contain free aluminum. In the case of small overloads and small lengths of sample it has the form of spheres with dimensions up to 100 μ, at large overloads and long lengths – it takes the form of flat cakes with a thickness of up to 1 mm.

The external appearance of the slag testifies to the fact that during the process of burning it is found in a liquid state. The ratio of the mass of the slag which remains in the cup (M) to the mass of the sample (M_0) is increased with an increase of acceleration. For samples with a length of 1.5 cm the ratio of $M/M_0 = 10^{-4}$ a/g is obtained.

Let us examine the model of the process of combustion of aluminized fuel in a field of accelerations. If a sample of fuel with a weight fraction of aluminum (W) burns with a mass velocity ρu, then from the condition of equality of gas-dynamic and inertial forces which act on a drop of aluminum oxide it is possible to determine the minimal radius of the drops which are pressed to the burning surface

$$r_{\text{мин}} = \sqrt{\frac{9\rho u(1-W)\eta}{\rho_\text{к}\rho_\text{г} a}}, \qquad (1)$$

where $\rho_{н}$ – density of a drop;

$\rho_{г}$ and η – density and viscosity of combustion products.

From the very same condition it is possible to write the expression for the magnitude of the gap between the drop and the surface of the fuel [1]

$$\delta = 0{,}7\,\rho u (1 - W) \sqrt{\frac{r}{\rho_{к} \rho_{г} a}}. \quad (2)$$

Thanks to the transmission of heat from the burning drops to the surface of the fuel the rate of combustion is increased.

An analogous explanation of the effect of an increase in the rate of burning during overloads is proposed in work [1], however, the calculation given there is open, since the particle size remains undetermined. In the present work a closed model is constructed which makes it possible to calculate the upper and lower boundaries of the rate of burning in a field of accelerations. From an analysis of the model it follows that in proportion to the combustion of the sample the rate is initially increased from the value u_0 (in the frames of the model we accept $u_0 = u|_{a=0}$) up to a maximum, and then it is reduced to a stationary value $u(l \to \infty)$. The initial sector up to the maximum of velocity is explained by the joining of the cones, in the apexes of which are found the drops (this sector we did not observe experimentally). Then in proportion to the blending and enlargement of the drops their distance from the surface increases, and, consequently, the rate of burning is reduced (Fig. 1).

When a drop reaches a certain size its surface becomes unstable. The maximum size of a drop $r_{мак}$ is determined by the fact that from its surface small drops (with $r < r_{мин}$) are torn off which are carried off by the flow. The expression for $r_{мак}$ can be written, stemming from the formula obtained in [2]:

$$r_{мак} = 0{,}25\, \sigma \rho_{г}^{0{,}5} \left[(u\rho)(1 - W) \eta \rho_{к} a \right]^{-0{,}5}, \qquad (3)$$

where σ – surface tension.

After this the size of a drop is not increased any more, and a stationary burning rate is reached.

The connection between the rate of combustion u and the temperature gradient $\varphi(u^2 = u_0^2 + k_1^2\varphi^2)$, originating from the theory of combustion of Ya. B. Zel'dovich, can be written in the form $u^2 = u_0^2 + k^2\delta^{-2}$. From here we obtain the bond $z = \frac{u}{u_0}$ with a particle radius r:

$$z^2(z^2 - 1) = \frac{2k^2 \rho_к \rho_г a}{(1 - W)^2 \rho^2 u_0^4 r}, \qquad (4)$$

where

$$k = \frac{\lambda_г (T_к - T_п)}{\rho c (T_п - T_0)};$$

$\lambda_г$ – thermal conductivity of gas;

c – heat capacity of fuel;

$T_к$; $T_п$ – temperature of drop and surface of fuel;

T_0 – initial temperature of sample.

It is evident that $z_{мак} = z(r_{мин})$ and $z_{мин} = z(r_{мак})$. Actually our experimental data and that of other authors [3-5] are found within these limits (Fig. 2).

Water-filled granular systems in the field of terrestrial gravitation burn in a turbulent or laminar mode. In the laminar mode the burning frequently attenuates, since the grains are filled with water [6, 7].

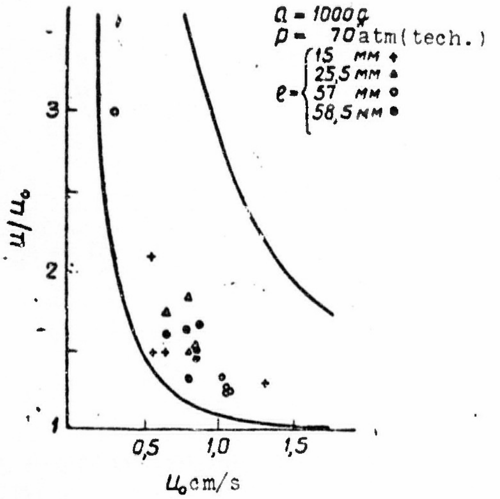

Fig. 2. Relative rate of burning at 70 atm(tech.) depending on the initial velocity. Dots – experiment, curves of extreme rates – theory.

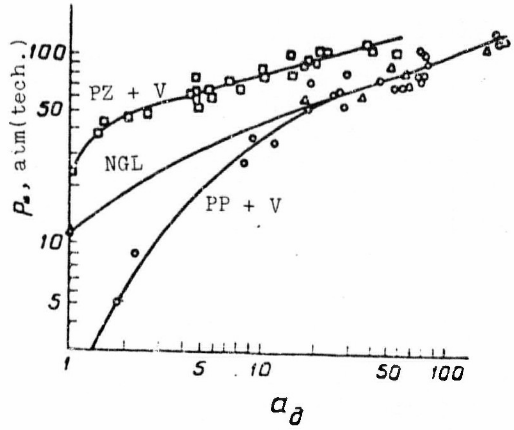

Fig. 3. Dependence of critical pressure of transition of laminar burning on acceleration.

In our tests a quartz tube 8 mm in diameter and 45 mm in length, filled with powder cylinders (h = d = 3 mm) and water (we abbreviate this system by PZ + V), was placed in a centrifuge. The sample was ignited close to the center of rotation; the burning front was shifted into the area of large accelerations, at a certain value a the burning converted from a turbulent into a laminar mode, and, as a rule, the extinction of the sample took place. Based on the measurements of the length of the remaining part of the sample and on the pressure oscillogram the extreme value of a at the given pressure was determined.

In proportion to the increase in acceleration there is an increase in the critical pressure p_* delimiting the area of turbulent ($p > p_*$) and laminar ($p < p_*$) burning (see curve PZ + V in Fig. 3).

In an analogous manner the limits were obtained for the turbulent burning of a model system consisting of two plates of powder (u = 16 mm/s at 60 atm(tech.), ν = 0.75). The width of each plate was 10, length 45, and thickness 1 mm; the gap between

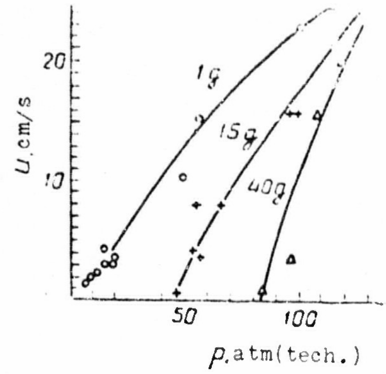

Fig. 4. Dependence of $u_{турб}$ of a slotted charge on p at various a.

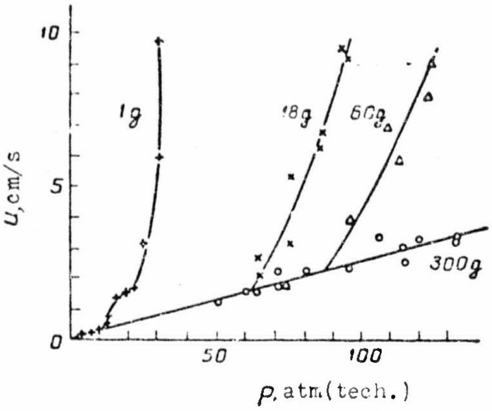

Fig. 5. Dependence of the rate of burning of nitroglycol on the pressure at various accelerations.

the plates (0.2 mm) was filled with water (we abbreviate this system by PP + V).

Accelerations, as it was predicted in work [7], promote the stabilization of burning, whereupon at $a \lesssim 10$ g, $p_* \sim a^2$ (see the curve PP + V in Fig. 3), as this also follows from theory [7]. However, at $a \gtrsim 10$ g the critical pressure increases more slowly ($p_* \sim a^n$, where $n \simeq 0.3$), which is possibly connected with a decrease in the characteristic length of the wave of unstable disturbances. With a > 10 g the form of the curves for the systems PP + V and PZ + V is analogous.

In addition to the value of critical pressure for the system PP + V the rate of turbulent burning was measured at various accelerations (Fig. 4).

Liquid VV — nitroglycol — was burned in quartz tubes with $d_{внут}$ of 5.5 mm. It was ignited by a plate of ballistite powder with a thickness of 0.5 mm.

At a = g the transition of burning to the turbulent mode took place at 12 atm(tech.) (Fig. 5), which agrees with the data of other authors [8].

With $a = 18$ g the critical pressure is equal to 60 atm(tech.), and with $a = 60$ g $p_* = 80$-90 atm(tech.). At accelerations higher than 300 g burning was laminar in the entire range studied (up to 140 atm(tech.)).

As predicted by the theory of L. D. Landau, acceleration stabilizes burning. It follows from the formula of Landau that for nitroglycol ($\nu = 1$) $p_* \sim a^n$, where $n = 0.5$. Experimental data (see the curve NGL in Fig. 3) are found in satisfactory agreement with this relationship.

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